We note that in $CrBr_3$, there is a large anisotropy in the strength of the Heisenberg exchange coupling between different pairs of neighbors.[4,6] There is also a rather large anisotropy field.[15] Both of these can be expected to influence the behavior of the magnetization near T_c.

The authors acknowledge with thanks the valuable help of Professor P. Heller in many aspects of this investigation. The samples were generously provided by Professor A. Smakula and Dr. J. I. Harrison. Computational work was done at the MIT Computation Center.

*This work was supported in part by the Advanced Research Projects Agency under Contract No. SD-90.

†National Science Foundation Graduate Fellow.

[1]I. Tsubokawa, J. Phys. Soc. Japan 15, 1664 (1960).

[2]A. C. Gossard, V. Jaccarino, and J. P. Remeika, Phys. Rev. Letters 7, 122 (1961); J. Appl. Phys. Suppl. 33, 1187 (1962).

[3]S. D. Senturia, P. Heller, and G. B. Benedek, Bull. Am. Phys. Soc. 8, 592 (1963).

[4]A. C. Gossard, V. Jaccarino, E. D. Jones, J. P. Remeika, and R. Slusher, Phys. Rev. 135, A1051 (1964).

[5]S. D. Senturia, thesis, Massachusetts Institute of Technology, 1966 (unpublished).

[6]H. L. Davis and A. Narath, Phys. Rev. 134, A433 (1964).

[7]G. B. Benedek and T. Kushida, Phys. Rev. 118, 46 (1960).

[8]G. K. White, Experimental Techniques in Low-Temperature Physics (Oxford University Press, London, 1959), p. 115.

[9]R. G. Barnes and S. L. Segel, Phys. Rev. Letters 3, 462 (1959).

[10]T. Kushida, G. B. Benedek, and N. Bloembergen, Phys. Rev. 104, 1364 (1956).

[11]P. Heller and G. B. Benedek, Phys. Rev. Letters 14, 71 (1965).

[12]P. Heller and G. B. Benedek, Phys. Rev. Letters 8, 428 (1962); P. Heller, Phys. Rev. 146, 403 (1966).

[13]L. D. Jennings and W. N. Hansen, Phys. Rev. 139, A1694 (1965).

[14]M. J. Buckingham, in Proceedings of the Conference on Phenomena in the Neighborhood of Critical Points, National Bureau of Standards, Washington, D. C., April, 1965 (to be published).

[15]J. F. Dillon, Jr., J. Appl. Phys. Suppl. 33, 1191 (1962).

STATISTICAL MODEL OF INTERMEDIATE STRUCTURE

J. J. Griffin*

Department of Physics, University of Wisconsin, Madison, Wisconsin
and Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received 31 May 1966)

A model is proposed for the formation and decay of the average compound-nuclear state in which a weak two-body residual interaction causes transitions among the eigenstates of an independent-particle Hamiltonian which lie in the region dE^* near the compound-nuclear excitation energy E^*. The independent-particle model states are classified according to the number of particles and holes (referred to indiscriminately as "excitons")[1] excited from the even-even ground state. The limitation on a two-body interaction, that it can only effect energy-conserving transitions which change the number of excitons by 0 or ± 2, is invoked and exploited to eliminate matrix elements which vanish identically. The details of the two-body interaction are suppressed (by replacing all nonvanishing matrix elements by an average value M) in order to exhibit most simply the dependence of decay probability on both the excitation energy of the compound nucleus and the excitation energy of the residual nucleus.

Decay is assumed to occur (in a very short time)[2] to a state with outgoing particle of energy E_0 and residual nucleus of energy U, whenever a nucleus makes a transition to an independent-particle state in which one exciton has energy E_0 in the continuum, and the remaining excitons share the energy $U = E^* - (E_0 + B)$, where B is the binding energy of the emitted particle. From a state described initially as a one-exciton independent-particle-model state (appropriate, e.g., for a reaction caused by one nucleon incident on an even-even target), the residual interactions cause successive transitions to 3-, 5-, 7-, $\cdots$-exciton states. At each such stage a small number of decays occur. These "precompound" decays are calculated in the present model.

They are found to describe (e.g., for neutrons) a "high-energy" tail similar to that observed in (p,n) reactions.[3] Finally, an equilibrium distribution results among the various independent-particle states, which is considered to describe "the average compound-nuclear state." Its decays are also calculated and are seen to resemble the usual "temperature" distributions qualitatively at any particular compound excitation energy E^*, but to depend both on E^* and on the residual nuclear excitation U.

As a model nucleus we assume that single-particle states occur with a density g per MeV.[4] Then at excitation energy E^* there are

$$\rho_n(E^*)=g(gE^*)^{n-1}/n!(n-1)! \quad (1)$$

n-exciton states per MeV and a total of

$$\rho(E^*)=\sum_n \rho_n(E^*) \quad (n \text{ odd or even with A}) \quad (2)$$

excited states per MeV. A nucleus in a typical n-exciton state makes transitions to other states with $n'=n$ or $n\pm 2$ excitons at a rate

$$\lambda_{nn'}=(2\pi/\hbar)M^2\rho_{n'}(E^*). \quad (3)$$

Since $\rho_n(E^*)$ is a rapidly increasing function of n for $n<\bar{n}=(gE^*)^{1/2}$, the probability is great that any n-exciton state (with $n \ll \bar{n}$) will make a transition into an $(n+2)$-exciton state. For simplicity, therefore, the transitions to $n'=n$, $n-2$ states are neglected in the precompound stages, and a system which is certainly in, say, a 1-exciton state initially is assumed during some stage of the approach to equilibrium to occur in each of the 3-, 5-, $\cdots$, $n \ll \bar{n}$-exciton states with a probability $1/\rho_n(E^*)dE^*$. In particular, it occurs among the $\rho_{n-1}(U) \times\rho_1(E_0)dE_0$ n-exciton states (which decay instantly by emitting a particle of energy E_0) with a probability

$$\rho_{n-1}(U)\rho_c(E_0)dE_0/\rho_n(E^*), \quad (4)$$

where $\rho_c(E_0)=2\pi(2m/h^2)^{3/2}(E_0)^{1/2}$ is the density of one-particle states in the continuum.

One thus obtains the "precompound" probability for emission of a particle E_0,

$$W_p(E_0)dE_0=\sum_{n>2}\frac{\rho_{n-1}(U)\rho_c(E_0)dE_0}{\rho_n(E^*)}$$
$$(n \text{ even or odd with } A), \quad (5)$$

or

$$W_p(E_0)\propto\frac{E_0^{1/2}}{E^*}\left[\frac{1+3r^2}{(1-r^2)^3}-1\right] \quad (n \text{ even}), \quad (5a)$$

$$\propto\frac{E_0^{1/2}}{E^*}\left[\frac{3r+r^3}{(1-r^2)^3}\right] \quad n \text{ odd}, \quad (5b)$$

where $r=(U/E^*)$. We have assumed here that this probability is so small that the total depletion due to such precompound decay can be neglected.

In the same framework, the rate of decay from the "compound-nucleus" equilibrium distribution can also be calculated from the probability of scattering into states $\rho_{n-1}(U)\rho_1(E_0)$ from states $\rho_{n'}(E^*)$, $n'=n, n\pm 2$, which at equilibrium comprise a fraction $\rho_{n'}(E^*)/\rho(E^*)$ of the whole system:

$$W_c(E_0)dE_0 = \sum_n \left(\frac{2\pi}{\hbar}M^2\right)\rho_{n-1}(U)\rho_c(E_0)dE_0 \times\frac{[\rho_{n-2}(E^*)+\rho_n(E^*)+\rho_{n+2}(E^*)]}{\rho(E^*)} \quad (6)$$

or, approximately,[5]

$$W_c(E_0)\propto f(E^*,U)\exp[4(g^2E^*U)^{1/4}], \quad (6a)$$

where

$$f(E^*,U) =E_0^{1/2}(E^*)^{19/8}(U)^{-11/8}[1+U/E^*+(U/E^*)^2]. \quad (6b)$$

The relative probability of observing a neutron of energy E_0 from a (p,n) reaction (e.g., at $E^*=E_p+B_p$) is then given by

$$W(E_0)\propto\alpha W_p(E_0)+W_c(E_0),$$

where α is a constant proportional to the fraction of "precompound" decays.

We note that W_c decreases exponentially with U, whereas W_p decreases only linearly for small U. This implies that W_p will dominate the distribution at low residual excitation energies, U, unless it is negligible everywhere. We have, therefore, plotted in Fig. 1 the ratio $N(E_0)/W(E^*,E_0)$ against U, utilizing for $N(E_0)$ the data of Wood, Borchers, and Barschall[3] from the (p,n) reaction on Sn^{117} (with $E_p=14$ MeV). One sees that this ratio does indeed remain constant for $U\le 6$ MeV, thus confirming the fact that $W_p(E^*,E_0)$ adequate-

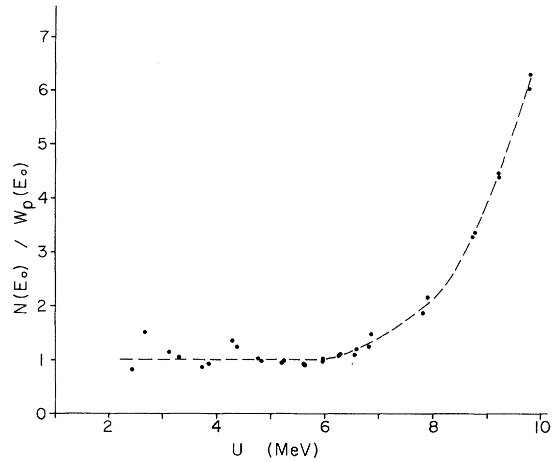

FIG. 1. The neutron distribution of Ref. 3 from the reaction $Sn^{117}(p,n)Sb^{117}$ at $E=14$ MeV is compared with the precompound distribution, $W_p(E_0)$. One sees that for residual energies below 6 MeV, W_p provides an excellent description of the observed distribution.

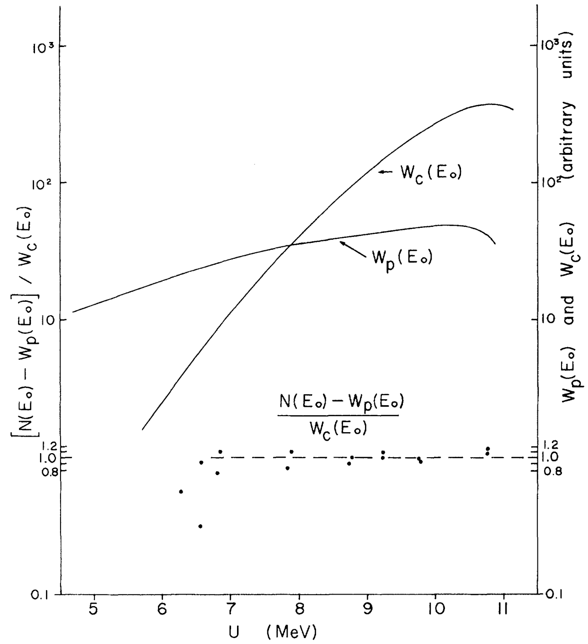

FIG. 2. The difference between the observed distribution (Wood, Borchers, and Barschall, Ref. 3) and the extrapolated precompound distribution is compared with the theoretical "compound" distribution for residual energies greater than 6 MeV. Perfect agreement would be indicated by a close clustering of points around the constant value of 1.0. Good agreement is evidenced for $8<U<11$ MeV.

ly describes the high-energy neutron tail. For higher residual excitations $N(E_0)$ rises exponentially, indicating that $W_c(E^*,E_0)$ dominates the low-energy neutron distribution, as its exponential increase would lead one to expect.

We test the details of Eq. (6a) by comparing

$$N_c(E_0)\propto N(E_0)-\alpha W_p(E^*,E_0) \tag{8}$$

with $W_c(E^*,E_0)$ where the constant, α, has been chosen so that the constant low-U ratio in Fig. 1 is equal to 1. In Fig. 2, we plot $N_c(E_0)/W_c(E_0)$ vs U, together with $W_c(E_0)$ and $W_p(E_0)$. The data cluster about a constant ratio (chosen to be 1) for residual excitations $U>7$ MeV. One sees here that the $U^{1/4}$ dependence of the exponent in W_c is not in disagreement with the data. The value implied for g is 11.

It would thus appear that the classification of the complexity of states according to the number of excitons provides a basis for resolving the conflict between the experimental facts and the usual statistical theory of nuclear reactions. This classification corresponds precisely to the hierarchy of doorway,[6] hallway,[7] and more complex states implicit in the intermediate structure theory of nuclear reactions.

Many other implications of this theory remain to be tested, and some work is already in progress in this direction. Perhaps the most obvious requirement is a systematic check of nuclear "temperature" data to see whether the distribution (6) agrees everywhere as well as it does in the $Sn^{117}(p,n)$ case.

The author is grateful to his colleagues at the Universities of Wisconsin and Maryland, and also to Dr. A. de Shalit, for their many stimulating comments, and especially to Dr. Wood, Dr. Borchers, and Dr. Barschall for their generosity in supplying their data for the comparisons exhibited in the figures.

---

*Present address: University of Maryland, College Park, Maryland.

[1]A more detailed treatment in which neutron and proton particles and holes are enumerated separately could easily be carried out. It would, however, add nothing to the illustrative purpose of the present report.

[2]This assumption is made primarily for simplicity. It would certainly be invalid for charged particles at energies so low that penetration through the nuclear Coulomb barrier significantly lengthens the lifetime of an unbound single-particle state against decay. The discussion here is relevant for processes emitting energetic neutrons. The generalization to other situations is straightforward.

[3]C. Holbrow and H. Barschall, Nucl. Phys. 42, 264 (1963); R. Wood, R. Borchers, and H. Barschall, Nucl. Phys. 71, 529 (1965); R. Borchers, R. Wood, and C. Holbrow, to be published.

[4]We here neglect a more detailed accounting according to good quantum numbers (a) for simplicity and (b) because such constraints lead to slow variations with energy of minor importance compared with the exponential dependences which exciton enumeration introduces.

[5]The approximation consists in expanding the logs of the summands in (6) near their maxima and replacing the summation by integration.

[6]A. Kerman, L. Rodberg, and J. Young, Phys. Rev. Letters 11, 422 (1963); A. Lande and B. Block, ibid. 12, 334 (1964); R. Lemmer and C. Shakin, Ann. Phys. (N.Y.) 27, 13 (1964); B. Block and H. Feshback, Ann Phys. (N.Y.) 23, 47 (1963).

[7]W. MacDonald and R. Ferrell, Phys. Rev. Letters 16, 187 (1966).

LARGE-ANGLE NEUTRON-PROTON C_{NN} PARAMETER AT 23.1 MeV*

J. J. Malanify,† P. J. Bendt, T. R. Roberts, and J. E. Simmons
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received 1 August 1966)

The neutron-proton spin-correlation parameter, C_{NN}, has been measured at $\theta_n = 140$ and 174° c.m., by scattering polarized neutrons from a polarized proton target. Comparison to recent phase-shift analyses is made, and a sensitivity of the S-D coupling parameter to the data is noted.

Neutron-proton scattering is dominated at low energy by triplet-S-wave scattering in isotopic $T=0$ states. The influence of the tensor force is felt through the mixing of $^3S_1$ and $^3D_1$ states in proportions determined by the mixing parameter[1] ϵ_1. Near 23 MeV other partial waves will be small, and will be reasonably close to their one-pion-exchange (OPE) values. Although it was not anticipated originally, the experiment described herein has shown a definite sensitivity to ϵ_1. The possibility of such behavior has been noticed previously by Batty.[2]

These data are timely in view of recent activity in empirical phase-shift analyses for the nucleon-nucleon system in which n-p as well as p-p data have been included. Among these, a series of single-energy phase-shift analyses has been done at Livermore spanning the energy range from 25 to 300 MeV; their work at 25 and 50 MeV has been reported by Noyes et al.,[3] and with small revisions by Arndt and MacGregor,[4] who also give energy-dependent forms for the phase shifts. Kazarinov, Kiselev, and Satarov[5] have published analyses in the range 26 to 126 MeV, while Batty and Perring[6] have obtained phase shifts at 50 MeV. The papers cited above agree that the coupling parameter, ϵ_1, has been poorly determined in the low-energy range. A similar observation was made in the prior energy-dependent phase-parameter analysis of the Yale group, where Hull et al.[7] reported that the solution called YLAN3 gave a negative value of ϵ_1 in the neighborhood of 50 MeV, while YLAN3M resulted in a positive value. Such behavior is not unexpected in view of the small data selection that has been available for n-p scattering below 100 MeV. In the latest development, a report has been received from Dubna by Bilenkaya et al.[8] giving the most recent results of their phase-shift analysis at 23 MeV. Not surprisingly, their value of ϵ_1 is in apparent disagreement with the results of Refs. 4 and 5.

The results of this experiment[9] were obtained by scattering polarized neutrons from a polarized proton target, and detecting the recoil protons in a counter telescope. This method is limited to small angles for proton emission, corresponding to large neutron scattering angles. The general features of the experimental setup are described briefly as follows: The reaction $T(d,n)He^4$ was used at an incident energy $E_d = 7$ MeV to provide neutrons at an angle $\theta_1(\text{lab}) = 30°$, with energy $E_n = 23.1 \pm 0.15$ MeV, and polarization[10] $p_1 = 0.49 \pm 0.06$. The cryostat, containing the polarized target, is positioned between the vertical pole faces of an electromagnet, and located such that the LMN[11] sample is at a distance of ≈ 25 cm from the neutron source at an angle $\theta_1 = 30°$ down. Proton polarizations averaging $p_2 \approx 0.30$ were obtained by the method of Abragam[12] and Jef-